Overlooked model uncertainties may misinform forest management strategies

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Abstract—still need work: Forests play a major role in mitigating climate change, but increasing threats to forests from climate change have heightened the importance of managing these systems. Robust forecasts of forest composition with increasing climate change are critical to this aim, but are currently highly variable. To help guide management in the face of this variability and understand where we can most rapidly reduce uncertainty through improved models, we compare over 1350 ecological models and climate scenarios in forecasts for forests across Europe. Our approach considers a gradient of more mechanistic ('process-based') to correlative models of species distributions to find that uncertainty in ecological models can drive more variation than vastly different climate scenarios (e.g., SSP2 vs. SSP5), but also areas with relatively consistent projections [give overview of these and say that this could reduce uncertainty in how to manage for these areas]. [Maybe something on using existing range data leads to more pessimistic forecasts?] Our results highlight a new way to approach ecological forecasting that better identifies areas of higher certainty and, conversely, the areas where managers will need more diversified approaches and where more ecological study may be most useful.

Main

Forests are key to pursuing climate change mitigation policies and achieving carbon neutrality[1,2]. Yet, forests are increasingly under pressure. In Europe, temperatures are rising twice as fast as the global average[3], and unprecedented pulses of tree mortality have been reported in the last decade[4]. As a result, some European forests are becoming net CO_2 sources[5,6], due to decreased growth[5,7], larger burned areas[8,9], and increased pest- and drought-induced dieback[6,10,11]. Forest managers are facing unprecedented challenges, as they must address current threats while also promoting long-term adaptation to climate change. In this context of high uncertainty, better guidance is needed to implement successful strategies.

Given the diversity of predictive ecological models, the challenge of providing practical insights for forest management is even greater. Different models, ranging from correlative to more mechanistic approaches, may provide highly divergent projections[12–15]. While it remains unclear under which conditions one approach is more reliable than another[16], most projections still rely on a limited set of models[17–20], ultimately increasing the risk of policy and management failures[21]. We often lack a robust estimation of uncertainty and a comprehensive understanding of what drives differences between projections[22]. Given the urgency of climate change, we must incorporate the diversity of models and merge across ecological and climatological models to provide a complete picture of both the threats and opportunities for forests.

Gaining a better understanding of where uncertainties originate and how they relate is crucial to identify opportunities to address policy-relevant questions[23–25]. Species shifts are predicted to have major impacts on timber production and on the forest economic sector[18,19]. Forest managers need to know whether the current species will be able to tolerate future climate conditions, whether they can rely on its natural regeneration, or whether they should capitalize on new species opportunities. If the main driver of variation across projections is the different

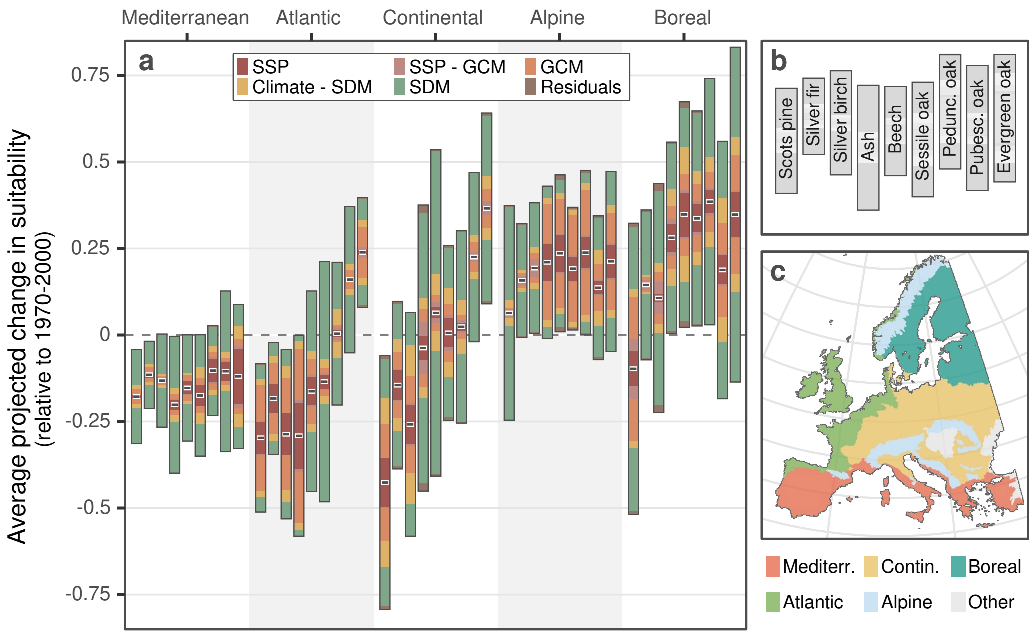

Figure 1: Ecological models represent the main source of uncertainty in future projections of species climatic suitability across European biomes (2080-2100).

ecological models, even more than different global emissions scenarios, it becomes critical to encompass the a wide range of models. Failing to do so could lead to overly confident predictions about which species will or will not be able to survive in future climates, ultimately leading to counterproductive or even detrimental forest management decisions.

To understand the level of confidence we can place in predictions requires a framework that account for all the various components of climatological and biological uncertainties, including socioeconomic scenarios, global climate models, ecological models, down to the species level. To this aim, we combined over 1350 projections of forest tree species distributions, incorporating a wide range of models, from more mechanistic ('process-based') to correlative models. Fully accounting for our current level of knowledge about future climate states and species functioning allows us to quantify the contribution of each component to the total variation across projections. This approach represents a significant advancement over previous studies, which overlooked large portions of uncertainty, and will lead to better informed decision-making to improve the resilience of forests.

Results and discussion

Our dataset included 9 tree species, both deciduous and coniferous, adapted to diverse climatic conditions across Europe. We simulated their suitability from 1970 to 2100, at a 0.1° spatial resolution, using a diverse set of ecological models spanning different hypotheses and calibration methods. We used 10 different future climate simulations, based on 2 forcing scenarios and 5 global climate models with different climate sensitivities.

Across species, ecological models drive more variation than vastly different climate scenarios (Figure 1). They consistently represent the main source of uncertainty across major European biomes (explaining between 42.9% and 63.9% of the variation between projections), with the exception of the Alpine biome. At the species-level, across all biomes, the differences between ecological models is also the main source of uncertainty for all the species considered here, and represents between 40% and 62% of the total uncertainty on average. One of the striking example is the climatic suitability change of sessile oak in the Atlantic region, where this species represents an important cultural and economic value, and for which more than 80% of the uncertainty in

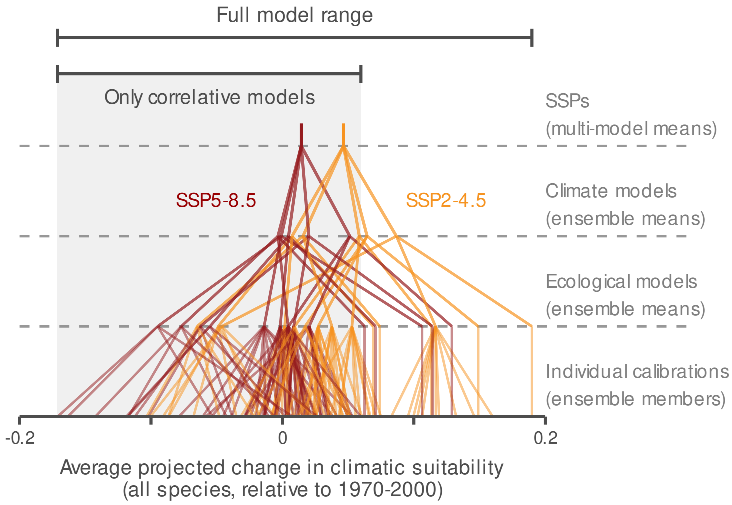

Figure 2: Considering a broad range of models provides a more comprehensive view of possible future scenarios.

climate change impact projections was due to variations among ecological models.

Failing to account for a broad range of ecological models severely underestimate projection uncertainty, and ultimately lead to incorrect trend estimates (Figure 2). Considering only correlative models would have misled to an overestimation of the contribution of climate projections (forcing scenarios, climate models, and their two-way interaction) to the total projection uncertainty in all regions, except the Mediterranean. In particular, divergence between climate models would have appeared to contribute as much as ecological models to projection uncertainty (on average, 36.6% and 37.5%, respectively). When accounting for more diverse ecological models, as done in our study, the uncertainty introduced by different ecological models (51.0% on average for all species) becomes greater than that introduced by climate models (19.9%). One of the key challenges for reducing uncertainty thus remains at the biological and ecological levels, even before considering the broad variations across future climate projections.

Our results also revealed that the divergence between ecological model projections followed a regular pattern. Models calibrated using current species range data consistently predict greater extinctions than models calibrated using experimental data (Figure 3). Current distribution data may capture only a portion of the climatic niche of a species, underestimating the range of conditions where it could survive[26,27]. These discrepancies between models can significantly alter country-level projections, and impact national strategies derived from them. For example, by the end of the 21st century, beech showed an average suitability decrease of -0.19 ($\pm$0.14) across its historical distribution when considering only models entirely calibrated with current species distribution data, leading to an average loss of 30.5% of its historical distribution (Figure 3). But this decreasing trend vanish once a broad range of models is accounted for (-0.028 $\pm$0.17). Relying on a narrow set of models—especially derived from the same calibration process—undermines the robustness of projections[21], and may ultimately bias decisions towards intensive intervention strategies (e.g. introduction of species outside their native range), potentially overlooking alternative strategies.

Despite large uncertainties, comparing diverse models improve prediction robustness and enable to identify areas with relatively consistent projections that differ in terms of future climate risks and levers of action to address them (Figure 4). Around the Mediterranean Basin, the models consistently predict less favorable climatic conditions for the species we considered here. In areas where most species are threatened, forest managers may thus consider introducing more drought-tolerant species. Along the Atlantic margin, the suitability of most species is also projected to decrease, except for the two Mediterranean species—pubescent and evergreen oaks— which could replace less adapted temperate species such as beech[28]. Mechanistic model

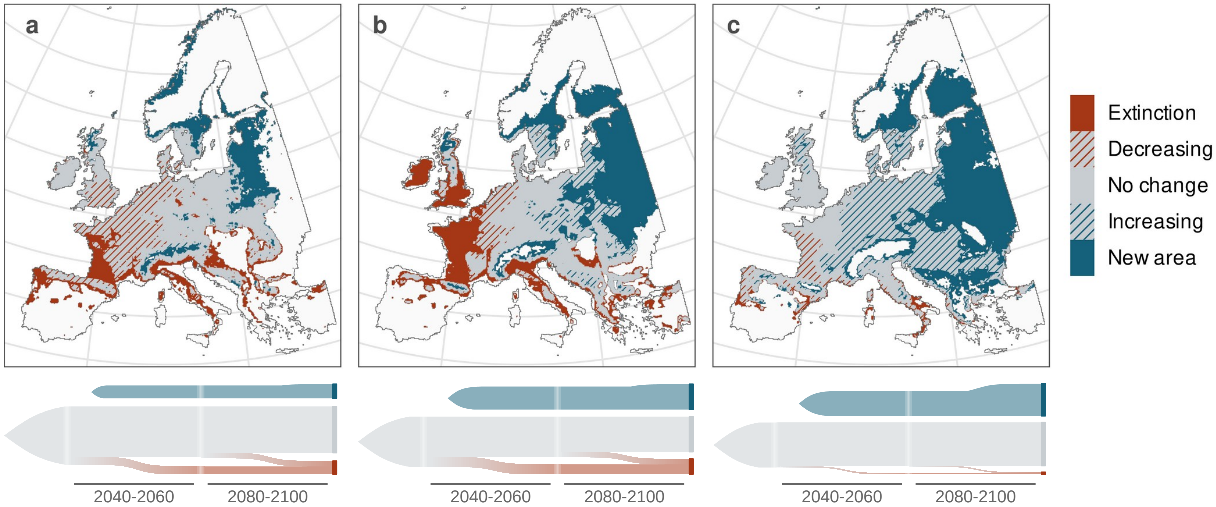

Figure 3: Models build on current species range data project higher extinctions. Example with beech, SSP2, 2080-2100.

projections are less pessimistic for deciduous oaks and beech (Figure 3), suggesting that some better-adapted populations could survive if the existing standing genetic variation is maintained and promoted by forest managers[29]. Additionally, adapting management practices, such as decreasing stand density to limit competition for water, could support their long-term survival to drought events[30].

A large part of the Continental biome exhibit less clearer trends (Figure 4), as well as mountainous regions at the transition between Mediterranean and Continental/Atlantic climates (Pyrenees, Massif Central, Balkans). Yet, looking at divergence across projections still provide important insights into species and locations most likely to experience significant changes in future climatic conditions. Models agree on a lower suitability for Scots pines (with uncertainty driven more by climatic models and scenarios, 45.7%, than by ecological models, 30.8%), which is a commercially very important species [cite] in several countries of Central Europe (such as Poland, Eastern Germany, Czech Republic, Belarus). Projections also suggest that temperate deciduous species (e.g. beech, deciduous oaks) will be less affected by climate change, despite high uncertainties due to high divergence among ecological models (between 45.7 and 75.4% of the total uncertainty). A key lever of action in this region is the diversification of tree species, as well as increasing genetic diversity within populations, to mitigate the risks associated with uncertain future conditions[31–34]. Promoting uneven-aged stands could also enhance forest stability by improving structural complexity and buffering against climate extremes[35,36].

Finally, boreal biomes in Scandinavian and Baltic countries are projected to get an overall increase of climatic suitability (Figure 4). These include Finland and Sweden, two very important forestry countries in terms of wood stock, added value, and forest-based workforce [cite]. Forests in these regions are dominated by two conifers species, Scots pine and spruce, favoured by commercial forest management. The lack of experimental data prevented us from making mechanistic model projections for spruce, but uncertainty for Scot pine future suitability was very high. Models consistently project that temperate deciduous trees will become more competitive at the northern margin of their range (Figure 3), and the extending growing season could offer an opportunity to convert pure coniferous stands into mixed forest to increase their resilience[37].

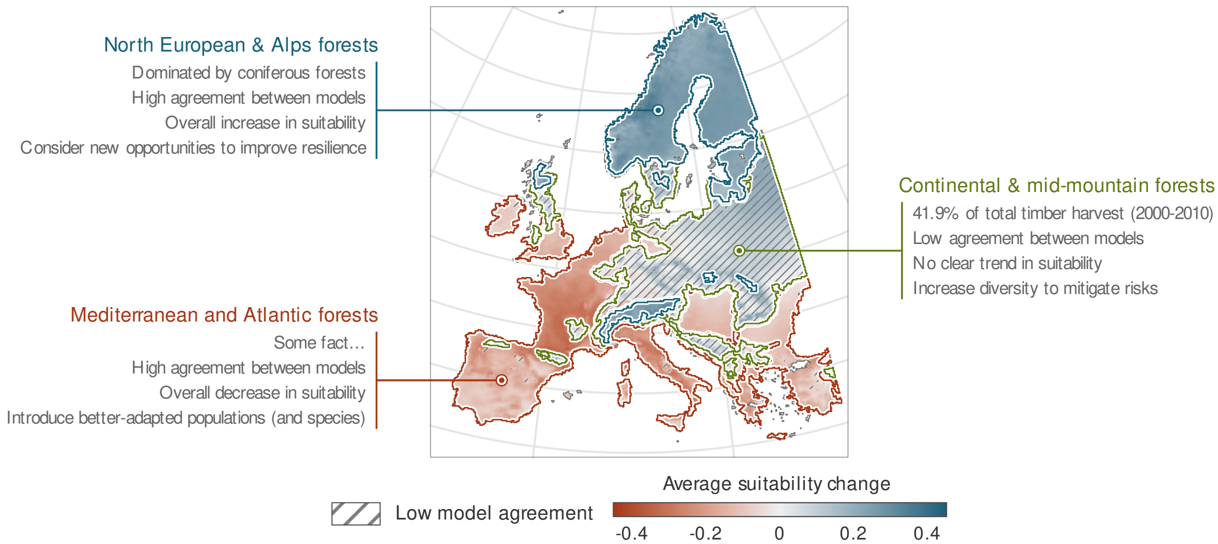

Figure 4: Accounting for uncertainties supports evidence-based forest management.

The implications of these results extend beyond European forests. The large uncertainties we found raise questions about the robustness of existing projections, and highlight that further advances are necessary to provide policy-relevant projections. Given the rapid pace of climate change, there is no time for fruitless debates over which modeling approach to favor. Instead, efforts should focus on bridging diverse methodologies to generate practical insights and support evidence-based decision making. Interdisciplinary synergies will be essential to developing models that are both grounded in mechanistic understanding and statistically robust. Correlative models may be refined by integrating experimental data[38]—yet, with some caution[39]. Mechanistic model improvements should go beyond mere sophistication—adding new processes and new parameters—toward robust statistical inference. Too often, mechanistic models often rely on a single immutable best-parameter set per species[40], preventing any proper propagation of uncertainty. Ultimately, as scientists, we need to be transparent about these uncertainties if we expect forest managers to acknowledge and integrate them[24]. This is how ecological modeling can become truly relevant to decision making in the face of a changing climate.

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